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Chandra Observations of the Stellar Populations and Diffuse Gas in Nearby Galaxies

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Abstract. We present *Chandra* observations of two star-forming galaxies (M 82 and the Antennae) and three starburst/AGN composite galaxies (NGC 1808, NGC 6240, NGC 7331). In both star-forming galaxies we detect a large number of sources with diverse properties. Some of them can be identified as X-ray binaries, based on their variability and spectra. However, there is a significant number of very soft and/or extended sources which could be supernova remnants. These observations confirm previous indications that there is a population of sources with X-ray luminosities much higher than the Eddington limit for a neutron star, suggesting that these objects are abundant in star-forming galaxies. We find the the X-ray luminosity functions of the discrete sources in these two galaxies are very similar. In the case of the composite galaxies we find that the AGN does not dominate their X-ray emission. A significant fraction of the emission from these objects is extended but there are also X-ray sources associated with circumnuclear star-formation.

1. Introduction

Earlier X-ray imaging observations of normal/star-forming galaxies, showed that their X-ray emission is very complex, arising from two different components: (a) discrete sources associated with supernova remnants (SNRs) and X-ray binaries and (b) diffuse gas often in the form of a superwind (e.g. Fabbiano 1989; Read, Ponman, & Strickland 1997). However, the relatively poor spatial resolution of these observations hampered any attempt to further study the properties of each component in detail. *Chandra* is revolutionizing this field by providing X-ray data over a wide energy band, with an unprecedented spatial resolution ($\sim 0.5''$). This spatial resolution is also critical to deconvolve the starburst and the AGN components in composite galaxies. We present the first results from *Chandra* observations of two well studied star-forming galaxies (M82 and the

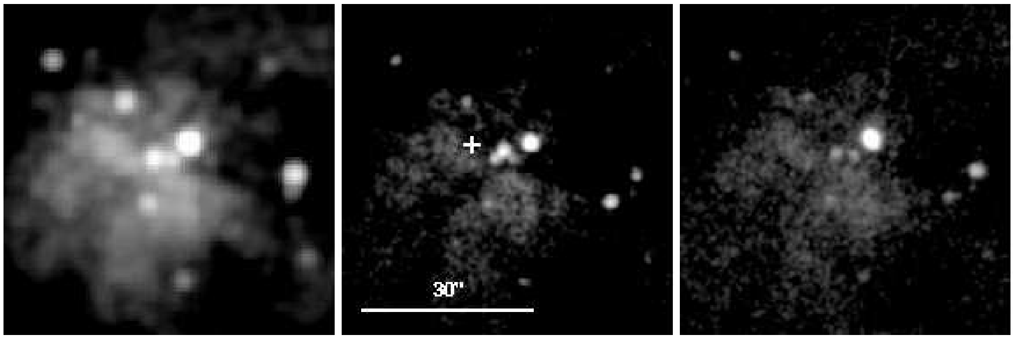

Figure 1. The central (0.9′ x 0.9′) region of M82 as observed in September 1999 (left), October 1999 (middle) and January 2000 (right). The first two images share the same color-map, whereas in the third the color-map is stretched in order to show the fainter sources. The cross in the second image marks the dynamical center of the galaxy. In this and the following images North is up and East is to the left.

Antennae) and three composite starburst/AGN galaxies (NGC1808, NGC6240 and NGC7331).

2. The star-forming galaxies: M82 and The Antennae

2.1. M82

The prototypical star-forming galaxy M 82, was observed on four occasions with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS-I), with exposures ranging between 5 and 15 ks. It was also observed twice with the *Chandra* High Resolution Camera (HRC). The *Chandra* observations show that there are 24 discrete sources down to a detection limit of $\sim 10^{37}$ erg s^{-1}. These sources comprise 10% of the total soft (0.3 - 2.5 keV) X-ray emission and 50% of the total hard (2.5 - 10.0 keV) X-ray emission of the galaxy. Twelve sources are found to vary by factors of 20 - 700% on timescales of 1 to 6 months, with the brightest of them reaching a peak luminosity of $\sim 10^{41}$ erg s^{-1}. The *Chandra* HRC observations of this extremely luminous source have been reported by Kaaret et al. (2000) and Matsumoto et al. (2000) and the first results from one ACIS-I observation are presented by Griffiths et al. (2000). Figure 1 shows three observations of the central kpc of M82 taken a few months apart. The first observation was performed with ACIS-I and the other two with HRC. The variability of some of these sources suggests that they most probably are associated with X-ray binaries (although, compact SNRs cannot be entirely dismissed). Three more sources are coincident with SNRs detected in deep radio observations. We constructed two cumulative X-ray luminosity function (XLF) of the sources in M82: one from the peak luminosity of each source and one from the longest observation. When fitted with a power-law they have comparable slopes ($\alpha = -0.40 \pm 0.04$ and $\alpha = -0.45 \pm 0.06$ respectively).

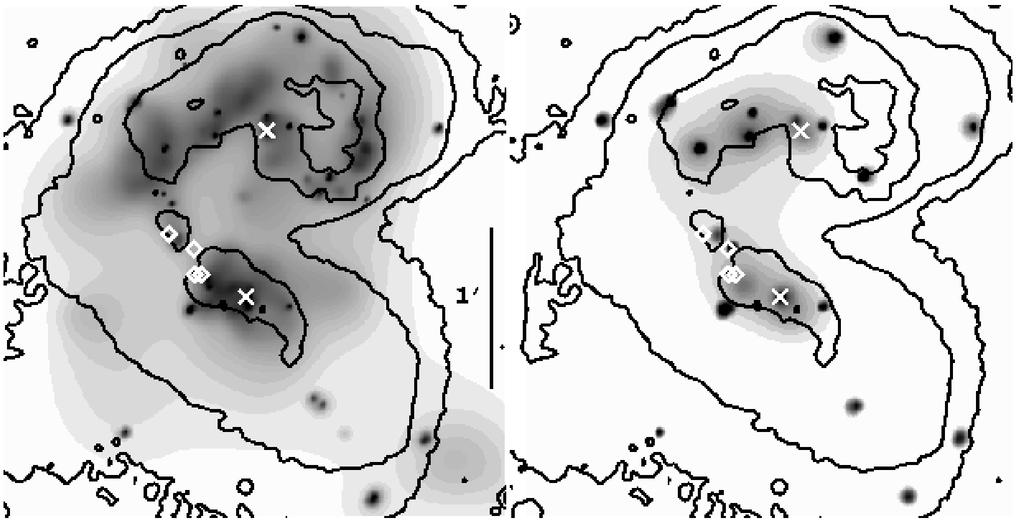

Figure 2. An adaptively smoothed soft (0.3-2.0 keV; left) and medium (2.0-4.0 keV; right) band X-ray image of the Antennae. The contours show the optical outline of the galaxy. The diamonds and the crosses show the position of the CO peaks and the two nuclei.

2.2. The Antennae (NGC 4038/9)

The Antennae are the prototypical example of merging galaxies. They were observed with ACIS-S for 72ks. We detect a total of 49 sources down to a detection limit of $\sim 10^{38}$ erg s^{-1}. The soft (0.3-2.5 keV) X-ray emission is mostly diffuse (68% of the total), whereas the hard X-ray emission (2.5-10.0 keV) is dominated by the discrete sources which account for $\sim 80\%$ of it. Figure 2 shows a soft and medium band image of the Antennae, with overlaid the optical outline of the galaxy. The first results from this observation have been reported by Fabbiano, Zezas, & Murray (2001). Two sources are found to be variable during this observation and two more sources are variable in timescales of a few years. The spectra of the discrete sources are very diverse. There is a marginally significant trend for the low luminosity sources to be softer than higher luminosity sources. The co-added spectra of the high luminosity sources ($L_X > 10^{39}$), are best fit with a multi-temperature disk black body model together with a power-law and a thermal plasma model, suggesting that most of them are associated with X-ray binaries. The inner temperature of the disk is ~ 1.3 keV, similar to what is found for other very luminous X-ray sources (eg Makishima et al. 2000). On the other hand the spectra of the sources with luminosities between 3×10^{38} erg s^{-1}and 10^{39} erg s^{-1}are well fit with a similar model but with a temperature of 0.25 keV for the inner part of the disk, which is more consistent with stellar size black holes. The XLF of the discrete sources in the Antennae galaxies has a slope of $\alpha = -0.45 \pm 0.05$, similar to what is found for M82. Finally, we find a total of 13 X-ray sources with one or more possible bright optical counterparts. All but 2 of the optical sources are young stellar clusters (age < 30 Myrs). We also find that 22 X-ray sources have one or more radio counterparts down to a flux level of ~ 40 μJy at 6 cm.

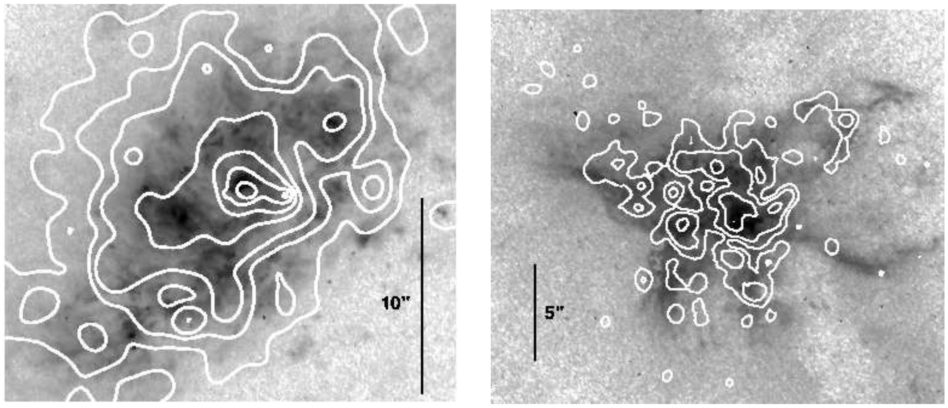

Figure 3. HST WFPC2 Hα images of NGC 1808 (left) and NGC 6240 (right) with overlaid X-ray contours from the HRC observation.

3. The composite galaxies: NGC 1808, NGC 6240 and NGC 7331

3.1. NGC 1808

NGC 1808 (fig. 3a) is a nearby (10.9 Mpc) composite galaxy. It has a circumnuclear star-forming ring with a radius of $\sim 5''$. In order to disentangle the starburst from the AGN component we observed it with the HRC-I for 25.5 ks. We find a point-like source coincident with the optical nucleus, with an X-ray luminosity of 1.2×10^{39} erg/s (0.1-10.0 keV), contributing only $\sim 10\%$ of the total X-ray emission of the galaxy. Apart from the nucleus we detect two more sources which are coincident with two HII regions in the circumnuclear starburst. These sources have a luminosity of 1.1×10^{39} erg/s and are embedded in diffuse emission. This diffuse component is most probably due to gas heated by the numerous supernovae in the starforming region.

3.2. NGC 6240

NGC 6240 is one of the best studied starburst/AGN composite galaxies. Previous X-ray observations showed that it hosts a highly obscured Compton thick AGN (Iwasawa & Comastri, 1998; Vignati et al. 1999). We observed this galaxy for 8.7 ks with HRC-I. We do not find a strong nuclear X-ray source; instead the nuclear emission is diffuse and has a luminosity of 2.4×10^{41} erg/s (for a distance of 100 Mpc), corresponding to 10% of the total emission. This is consistent with this nucleus being Compton thick, and suggests that we are viewing either scattered emission from the AGN or diffuse gas associated with the circumnuclear starburst. Since the HRC does not have any spectral resolution it is not possible to distinguish between these two possibilities. We do not find many discrete sources, which could be due to the large distance of NGC 6240 and to the relatively short exposure. However, we find a striking similarity between the H_α and the X-ray morphology (figure 3b). The most interesting feature is an arc with a luminosity of 1.7×10^{41} erg/s in the North-West of the nucleus also seen in H_α. This loop could be an outflow or a supershell associated with the circumnuclear starburst.

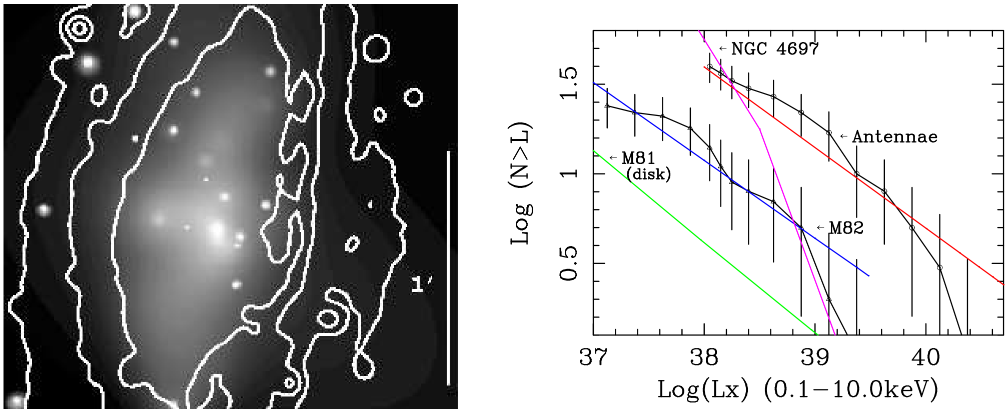

Figure 4. Left: An adaptively smoothed soft (0.3-2.0 keV) X-ray image of the central region of NGC 7331. The contours show the optical outline of the galaxy. Right: The cumulative XLF of M 82 and the Antennae shown together with the XLFs of NGC 4697 and M 81.

3.3. NGC 7331

NGC 7331 is a nearby (14.3 Mpc) composite galaxy. We observed it with the ACIS-S camera for 29.5 ks. Figure 4a presents the soft band (0.3-2.0 keV) adaptively smoothed image of the galaxy with its optical outline shown by the contours. We detect a total of 35 X-ray sources down to a luminosity threshold of $\sim 5 \times 10^{37}$ erg s^{-1}. The XLF of the discrete sources in this galaxy has a slope of $\alpha = -0.67$. This is steeper than the slope found for the starforming galaxies and closer to that of early type galaxies, suggesting that there is a significant contribution from a older X-ray source population.

4. Discussion and Conclusions

Chandra allows us to study the discrete source populations in galaxies outside the Local Group, in detail for the first time. The first results from these studies show two things: (a) The ultraluminous X-ray sources ($L_X > 10^{39}$ erg s^{-1}) previously found in nearby galaxies (eg. Fabbiano et al. 1989; Makishima et al. 2000), are quite common at least among star-forming galaxies; (b) the X-ray luminosity functions of the discrete sources in star-forming galaxies are different than those of early type galaxies.

In the case of M 82 and the Antennae we detect a total of 3 and 19 ultraluminous sources (ULXs) respectively. Although some of them could be compact SNRs (eg. Fabian & Terlevich, 1996), it is unlikely that most of them are associated with this class of rare objects. If these sources are not beamed, the compact object must be a black hole in the mass range $10 - 1000$ M$\odot$. The spectra of similar sources detected in other galaxies have been interpreted as evidence for accretion onto a Kerr black hole (eg. Makishima et al. 2001). Suggested models for the formation of these intermediate mass black holes, include: remnants of Population III stars (Madau & Rees, 2001), mergers of smaller black holes (eg. Taniguchi et al. 2000), and mergers of massive stars (Portegies-Zwart, 1999).

Another possibility is that the intrinsic luminosity of these sources is mildly beamed (King et al. 2001). In this case the compact object could be a stellar size black-hole or even a neutron star.

As presented previously, both the XLFs of M 82 and the Antennae have very similar slopes. This is more clearly seen if Figure 4b which shows the two luminosity functions as well as the XLFs of the early type galaxy NGC 4697 (Sarazin, Irwin, & Bregman 2001) and the nearby spiral galaxy M 81 (Tennant et al. 2001). In this figure we also see that the XLFs of the star-forming galaxies are similar to that of M 81, but very different from that of NGC 4697. This suggests that X-ray sources associated with a young stellar population (HMXBs) dominate in star-forming galaxies. Also, we see an excess of ULXs in the more actively star-forming galaxies (Antennae and M 82) in comparison to the less active M 81. Although this is very preliminary, it suggests that may be a correlation between the presence of ULXs and the level of star-formation activity in a galaxy.

The observations of the three composite galaxies presented here clearly show that the AGN does not necessarily dominate the X-ray emission of the galaxy. This could be due either to an intrinsically weak AGN (as e.g. in NGC 7331) or due to large obscuration (e.g. NGC 6240), as suggested by e.g. Fabian et al. (1998) and Levenson et al. (this volume).

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